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Charged particle spectra measured during the transit to Mars with the Mars Science Laboratory Radiation Assessment Detector (MSL/RAD)

Bent Ehresmann[a,*], Donald M. Hassler[a], Cary Zeitlin[b], Jingnan Guo[c], Jan Köhler[c], Robert F. Wimmer-Schweingruber[c], Jan K. Appel[c], David E. Brinza[d], Scot C.R. Rafkin[a], Stephan I. Böttcher[c], Sönke Burmeister[c], Henning Lohf[c], Cesar Martin[c], Eckart Böhm[c], Daniel Matthiä[e], Günther Reitz[e]

[a] *Southwest Research Institute, Space Science and Engineering Division, 1050 Walnut Street, Suite 300, Boulder, CO, USA*
[b] *Southwest Research Institute, Earth, Oceans, & Space Department, Durham, NH, USA*
[c] *Christian-Albrechts-Universität zu Kiel, Kiel, Germany*
[d] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*
[e] *Deutsches Zentrum für Luft- und Raumfahrt, Cologne, Germany*

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A B S T R A C T

The Mars Science Laboratory (MSL) started its 253-day cruise to Mars on November 26, 2011. During cruise the Radiation Assessment Detector (RAD), situated on board the *Curiosity* rover, conducted measurements of the energetic-particle radiation environment inside the spacecraft. This environment consists mainly of galactic cosmic rays (GCRs), as well as secondary particles created by interactions of these GCRs with the spacecraft. The RAD measurements can serve as a proxy for the radiation environment a human crew would encounter during a transit to Mars, for a given part of the solar cycle, assuming that a crewed vehicle would have comparable shielding. The measurements of radiological quantities made by RAD are important in themselves, and, the same data set allow for detailed analysis of GCR-induced particle spectra inside the spacecraft. This provides important inputs for the evaluation of current transport models used to model the free-space (and spacecraft) radiation environment for different spacecraft shielding and different times in the solar cycle. Changes in these conditions can lead to significantly different radiation fields and, thus, potential health risks, emphasizing the need for validated transport codes. Here, we present the first measurements of charged particle fluxes inside a spacecraft during the transit from Earth to Mars. Using data obtained during the last two month of the cruise to Mars (June 11–July 14, 2012), we have derived detailed energy spectra for low-Z particles stopping in the instrument's detectors, as well as integral fluxes for penetrating particles with higher energies. Furthermore, we analyze the temporal changes in measured proton fluxes during quiet solar periods (i.e., when no solar energetic particle events occurred) over the duration of the transit (December 9, 2011–July 14, 2012) and correlate them with changing heliospheric conditions.

1. Introduction

The Radiation Assessment Detector (RAD) (Hassler et al., 2012) is an energetic particle detector developed to measure the radiation environment on the surface of Mars as part of the Mars Science Laboratory (MSL) mission (Grotzinger et al., 2012). The MSL spacecraft was launched on November 6, 2011, landing in Gale crater on Mars on August 6, 2012. Since then RAD has been operating almost continuously, conducting the first-ever measurements of the Martian surface radiation environment (Hassler et al., 2014; Ehresmann et al., 2014; Köhler et al., 2014; Rafkin et al., 2014). Although characterizing the Martian radiation environment is the primary mission goal of MSL/RAD, the instrument was also operated for large parts of the trip from Earth to Mars. Situated on board the MSL rover *Curiosity*, RAD measured the radiation environment inside the spacecraft, motivated by the possibility that a human crew will someday encounter a very similar environment. First findings for the cruise phase measurements have been reported by Zeitlin et al. (2013), Guo et al. (2015a) and Köhler et al. (2015).

* Corresponding author.
E-mail address: ehresmann@boulder.swri.edu (B. Ehresmann).

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Mitigating risks to astronauts posed by the levels of radiation encountered during the transit to Mars and on the planet itself constitutes one of the most important factors for planning future crewed missions to Mars. This is because the radiation environment differs greatly from the one on Earth, where surface radiation levels are two to three orders of magnitude lower than in free space and on Mars (Zeitlin et al., 2013; Hassler et al., 2014) because of Mars' much thinner atmosphere and its lack of a global magnetic field. Not only is the intensity of the particle fluxes greatly different on Earth compared to space, so is the composition. On Earth, only singly-charged particles (predominantly muons) reach the surface, but in space the Galactic Cosmic Rays (GCRs) include high-energy ions of all species. Exposure to high levels of radiation (both on short- and long-term scales) can pose potential hazards to health and life (Baumstark-Khan and Facius, 2001). A detailed understanding of the radiation environment, as well as how it changes over time (e.g., over the course of the solar activity cycle), is thus of prime importance for the development of appropriate counter measures, such as shielded habitats, pharmacological interventions, and the potential use of active shielding. Furthermore, it is also critical for assessing the benefits of faster transit times, shielding, and the choice of time frame for the mission (Drake and W., 2010).

To be able to confidently predict what the expected radiation exposure would be for any proposed launch time and mission duration, radiation environment models must be validated with *in-situ* measurements to ensure their accuracy and predictive capability. RAD provides a unique contribution to this process. Current risk assessment tools that are in use consider the fact that the radiation effects depend on type and energy of the inducing radiation (Cucinotta et al., 2011), necessitating a detailed knowledge of particle spectra of different types of ion species. RAD was designed to measure energy spectra for different particle species (and groups) in limited energy ranges and integral fluxes for higher energies, enabling comparison of these data with model results.

Detailed spectral information is a standard output of most commonly used radiation transport models, e.g., Planetocosmics (Desorgher et al., 2006) or OLTARIS (Singleterry et al., 2011). Planetocosmics is an application for the Monte-Carlo particle transport code GEANT4 (Agostinelli, 2003), while OLTARIS combines the Badwhar-O'Neill GCR flux model (O'Neill, 2010) with the HZETRN transport code (Slaba et al., 2010). However, these models show discrepancies in their results both when compared to each other, as well as to the actual, measured RAD data (Ehresmann et al., 2014; Köhler et al., 2014; Matthiä et al., 2016), highlighting the need for extensive and continued *in-situ* measurements and model validation efforts. Furthermore, as shown by Mrigakshi et al. (2012), and as demonstrated in the analysis presented here, there are also significant uncertainties in existing GCR flux models.

In the following, we present differential energy spectra for isotopes of $Z = 1$ and $Z = 2$ ions, measured by MSL/RAD in June/July 2012 while in transit to Mars. We also present integral fluxes for different ion species in a higher energy range (from hundreds of MeV/nuc up). We also analyze the variability of the proton flux with time (from December 9, 2011 to July 14, 2012) and relate this to the changing solar modulation of the GCR flux, all with the idea to provide much needed input for the modeling community for their efforts in improving and validating the models.

2. Measuring charged particles with RAD

The RAD instrument and its capability for particle measurements have been described in detail in previous literature. A in-depth overview is given by Hassler et al. (2012). Measurement methods and nomenclature for charged particle measurements have also been previously reported in detail by

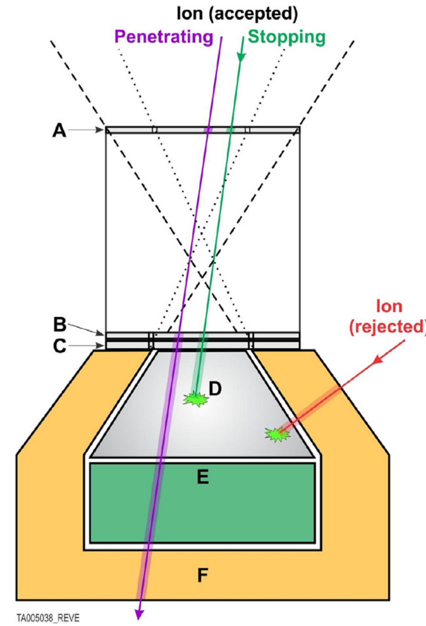

Fig. 1. Schematic of the RAD sensor head. Examples of valid flight paths for stopping and penetrating particles are shown in green and magenta, respectively. The red arrow indicates an ion with an invalid flight path. While it still stops in detector D, it did not enter the detector stack through the field-of-view spanned by detectors A and B. Taken from Ehresmann et al. (2014). A schematic detailing the segmentation of detectors can be found in Fig. 9 of Hassler et al. (2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Ehresmann et al. (2014). (For neutral particle detection the reader is referred to Köhler et al., 2011; 2014). Thus, only a brief overview of RAD and the most important features for the understanding of this publication is given here.

2.1. Instrument overview

The RAD Sensor Head (RSH) consists of several detectors: 3 silicon detectors (A,B, and C) in a telescope geometry, followed below by a CsI scintillator (D) and a plastic scintillator (E). The shape of the D detector was chosen so that it preserves the viewing cone defined by the $A \cdot B$ coincidence. D and E are enclosed by another plastic scintillator, F, that is divided into two segments F1 (on the sides of D and E) and F2 (at the bottom of E). A schematic drawing of the RSH can be seen in Fig. 1, while a schematic detailing the different segments of the detectors can be found in Hassler et al. (2014), and in particular Fig. 9 therein. The A detector (which consists of an inner segment A2 and an outer segment A1) is used in coincidence with the B detector to define the RAD field-of-view (FOV) and acceptance angle for charged particle detection. The B detector is also used to record Linear Energy Transfer (LET) spectra for $A \cdot B$ coincidence events. The D and E detectors are used for charged particle detection, and (in anticoincidence (AC) with C and F) provide efficient neutral particle detection. Different sensitivities of D and E allow for a distinction of neutrons and γ-rays (see Köhler et al., 2011; 2014). In the onboard software, running totals of energy deposits are recorded for detectors B and E (with no coincidence requirements), typically in 30-s or 1-min time intervals; these data are used in ground analysis to determine dose rates in silicon and plastic, respectively. E.g., the measured data are corrected for dose contributions from *Curiosity's* Radioisotope Thermal Generator (RTG) which were determined pre-launch, see Zeitlin et al. (2013).